Optimizing the Mix of Legacy and New Navigation Services

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Background

- The Very High Frequency Omnidirectional Range (VOR) is a ground-based Navigational Aid (Navaid).
- National Airspace System (NAS) contains a network of more than 1,000 VORs.
- The navigation and landing system will evolve from ground-based Navaid to a satellite-based navigation (SATNAV) system.
- During the transition to the SATNAV system, the FAA is planning to phase out some ground-based Navaids, including some VORs.
- Users not equipped with SATNAV avionics, will still rely on the VORs.
- Users equipped with SATNAV avionics may rely on the VORs for backups in case of disruption to the satellite-based system.

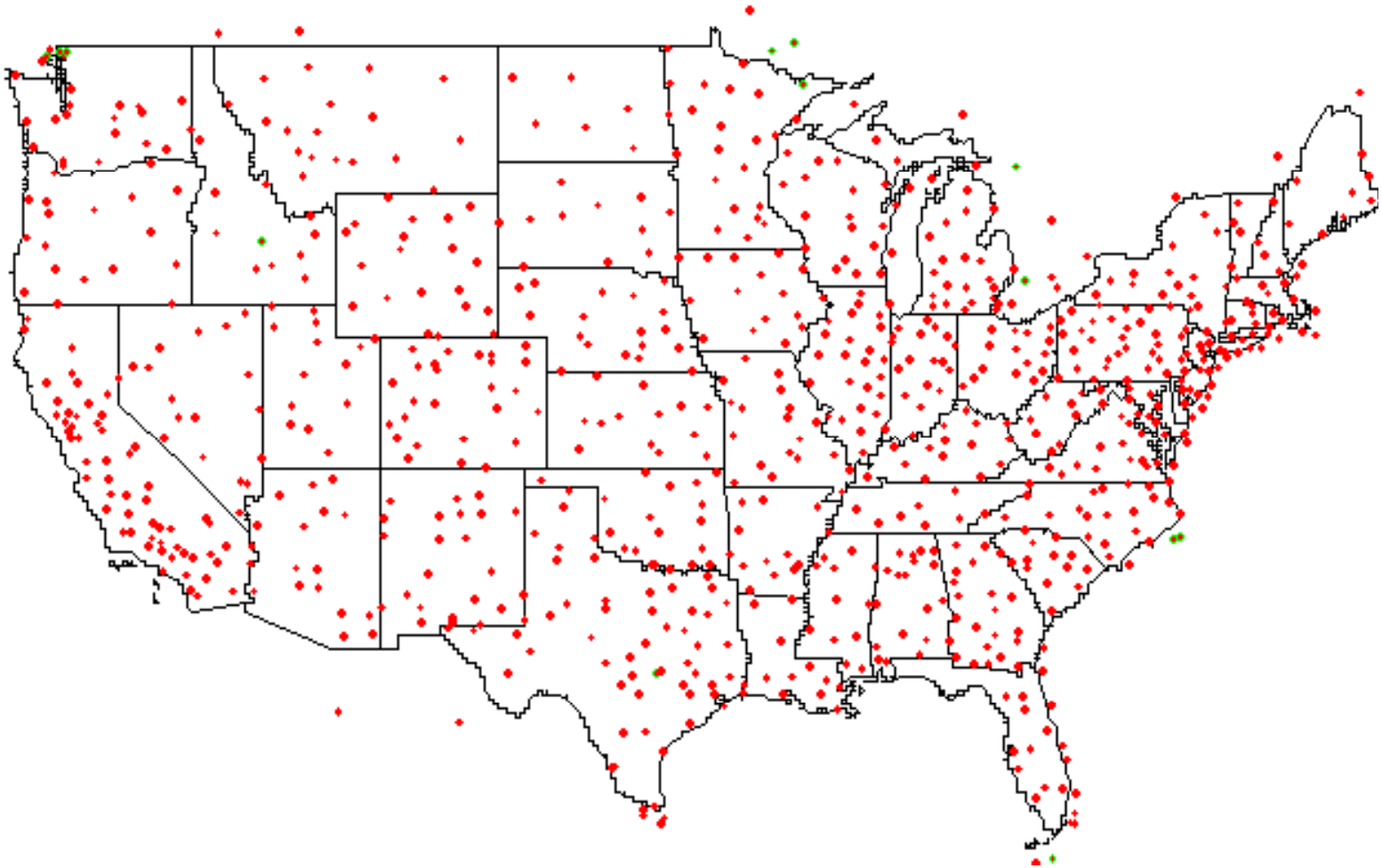
Question

- When is it cost effective to phase out VORs?
  - How many?
  - Which?
- What are impacts on flying public?
  - For non-equipped aircraft
  - How many and which city pairs will be disconnected from the VOR network?

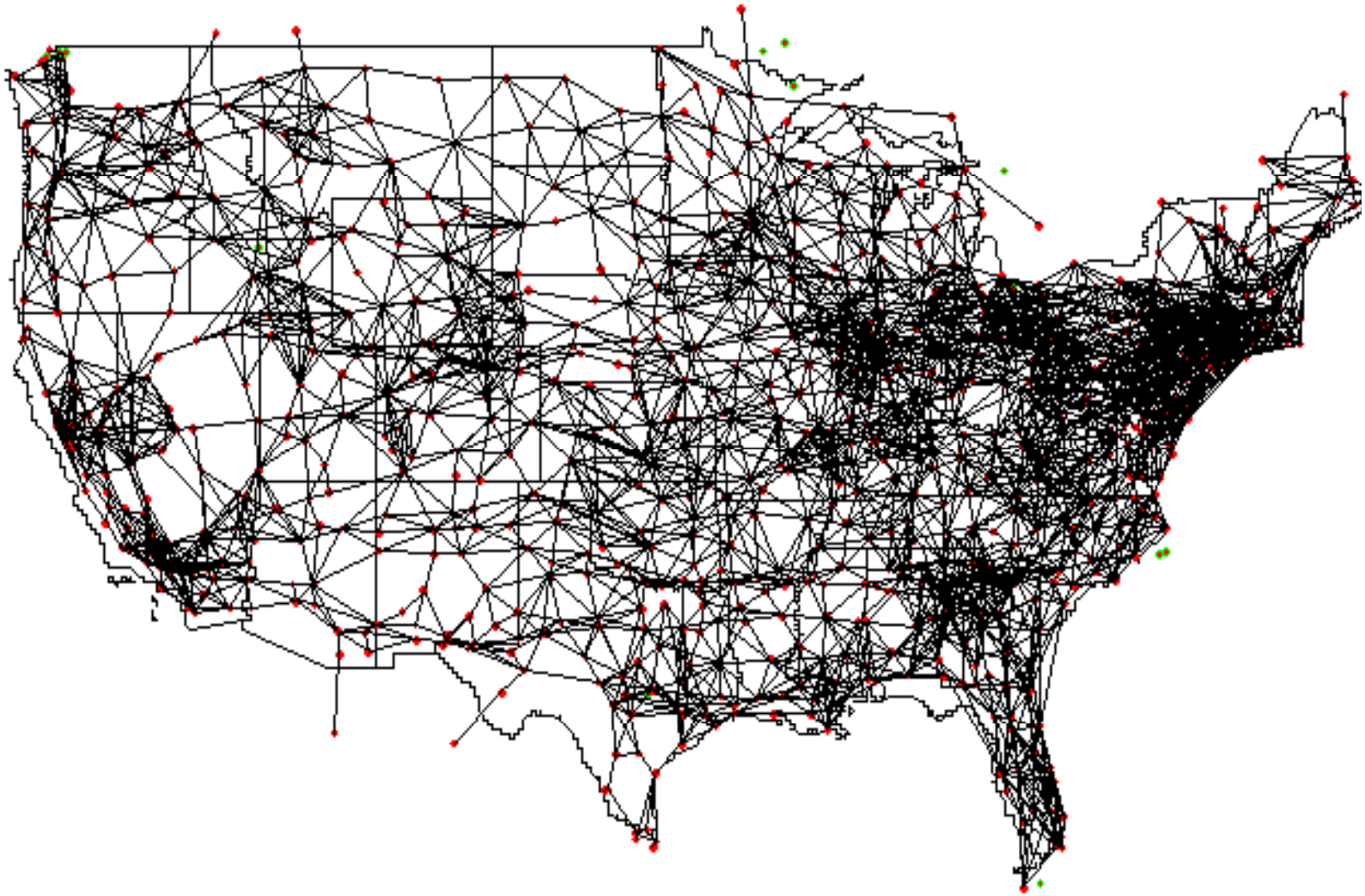
Network Modeling

- Network modeling using linear and integer programming:
  - Can be used either separately or as a complement to other approaches
  - Can aid decision-makers in establishing VOR discontinuance criteria
- Models can be designed to include appropriate cost-benefit aspects and determine set of VORs for decommissioning with minimal impact to FAA and NAS users.
  - Cost to the non-equipped users (commercial airlines and general aviation)
    - Cost of flying longer routes
    - Cost of equipping with SATNAV avionics to be able to fly between city pairs disconnected from the VOR networks
  - Cost of maintaining VORs
  - Cost of decommissioning VORs

Map of VORS



VOR to VOR Connections



Model Description

- Directed graph
- Over 5,000 nodes
  - Airports
  - VORs
- Arcs represent routes or paths traveled by NAS users - over 30,000 directed links
  - All existing flight paths are considered
- 55,000 city pairs have at least one flight
  - User classes include:
    - GA
    - Commercial
    - Freight and air taxi
  - Based on 12 days of Enhanced Traffic Management System (ETMS) data

Model Formulation

- **Objective Function** includes three cost components:
  - Cost of maintenance for VORs left open
  - Cost of decommissioning for the rest of VORs
  - Cost to users operating between all city pairs within the network
  - Avionics reconfiguration cost for disconnected flights
- **Decision variables**:
  - OPEN: binary variable is one if VOR remains open (~1,000)
  - CANCEL: number of flights disconnected for a city pair (~55,000)
  - TRAFFIC: corresponds to all links in the network for all city pairs
    - Equals to total operating cost/nm for a city pair, if flights associated with that city pair are not disconnected and the link is used in the flight path (derived by the model) for the city pair.
    - Originally over several billion variables. Variable reduction techniques reduced to a few million.

Model Formulation

- Constraints
  - If traffic flows into a VOR, then VOR must be kept open.
  - For all city pairs and VORs, flow in should equal flow out.
  - Flow out of all originating airports for all connected city pairs should equal demand.
  - Flow into all destination airports for all connected city pairs should equal demand.

Solving the MIP Problem

- Eliminating infeasible variables from TRAFFIC vector
  - **This is the most important and the biggest adjustment made to bring this MIP problem from a "too complex" status to a solvable status**
  - Description:
    - If the total travel cost through the VOR network using the shortest available path for a city pair is greater than the avionics reconfiguration cost, then the city pair is disconnected.
    - VOR-to-VOR link can be a candidate for use only by a flight between a given city pair, if the minimum cost of traveling through that link is less than the avionic cost. The minimum distance is defined as the overall shortest path through that link, assuming all VORs are open.
- Other variable reduction techniques:
  - Eliminating the unnecessary VOR-to-airport links and city pair variables.

Solving the MIP Problem (Cont'd)

- **Relaxation technique**: Adjustment made to solve mixed integer program as a linear program
  - This adjustment forces OPEN to be 1 or zero almost always without using binary variables. The trade-off is the increase in the number of constraints.
- Original constraint:

$$\sum_{l,(o,d)} TRAFFIC[(o,d),(l,k)] \le schedule[(o,d)] * OPEN[k] \qquad \forall k$$

- Reformulated constraint:

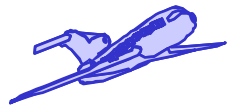
$$\sum_{l} TRAFFIC[(o,d),(l,k)] \le schedule[(o,d)] * OPEN[k] \qquad \forall k,(o,d)$$

where: *(o,d)* = a city pair,
k = a VOR
Schedule *[(o,d)]* = demand for city pair *(o,d)* and
(l,k) = a directed link between an airport or VOR*l* to VOR *k*

Solving the MIP Problem (Cont'd)

- Partitioning the city pairs
  - Started with ~10,000 busiest city pairs (92%) of demand
  - Obtained the optimized list of VORs left open
  - Forced the model to keep these VORs open and ran it for the remainder of city pairs (in 4,000 to 5,000 sets) over several runs
- Adjustments for efficiency (software specific)
  - Changing variable structures and definitions
  - Optimizing search procedures
  - Data preprocessing

Initial Result



- Results obtained using
  - Unequipped forecasted flights in 2011
  - Operating costs and SATNAV equipage rates (75%-85%) vary by user class.
  - VOR decommissioning costs amortized over 15 years.
  - Avionics reconfiguration costs amortized over 1 year.
- The most cost effective result using network modeling is achieved by decommissioning 113 VORs and disconnecting 36 flights from 405 city pairs.
  - The number of flights is lower than the number of city pairs because they reflect unequipped flights only.
- The number of decommissioned VORs is fewer than expected.

Summary

- Network modeling can be used to determine the set of VORs for discontinuance that has minimal impact to the NAS users and FAA.
- A large scale Mixed Integer Program (MIP) was built to solve the problem.
- This network contains over 5,000 nodes and over 30,000 directed arcs.
- Innovative ways to reduce the number of variables and linear relaxation techniques enable us to solve this large problem.
- Model is available to support future ground based NAVAID decommissioning scenarios

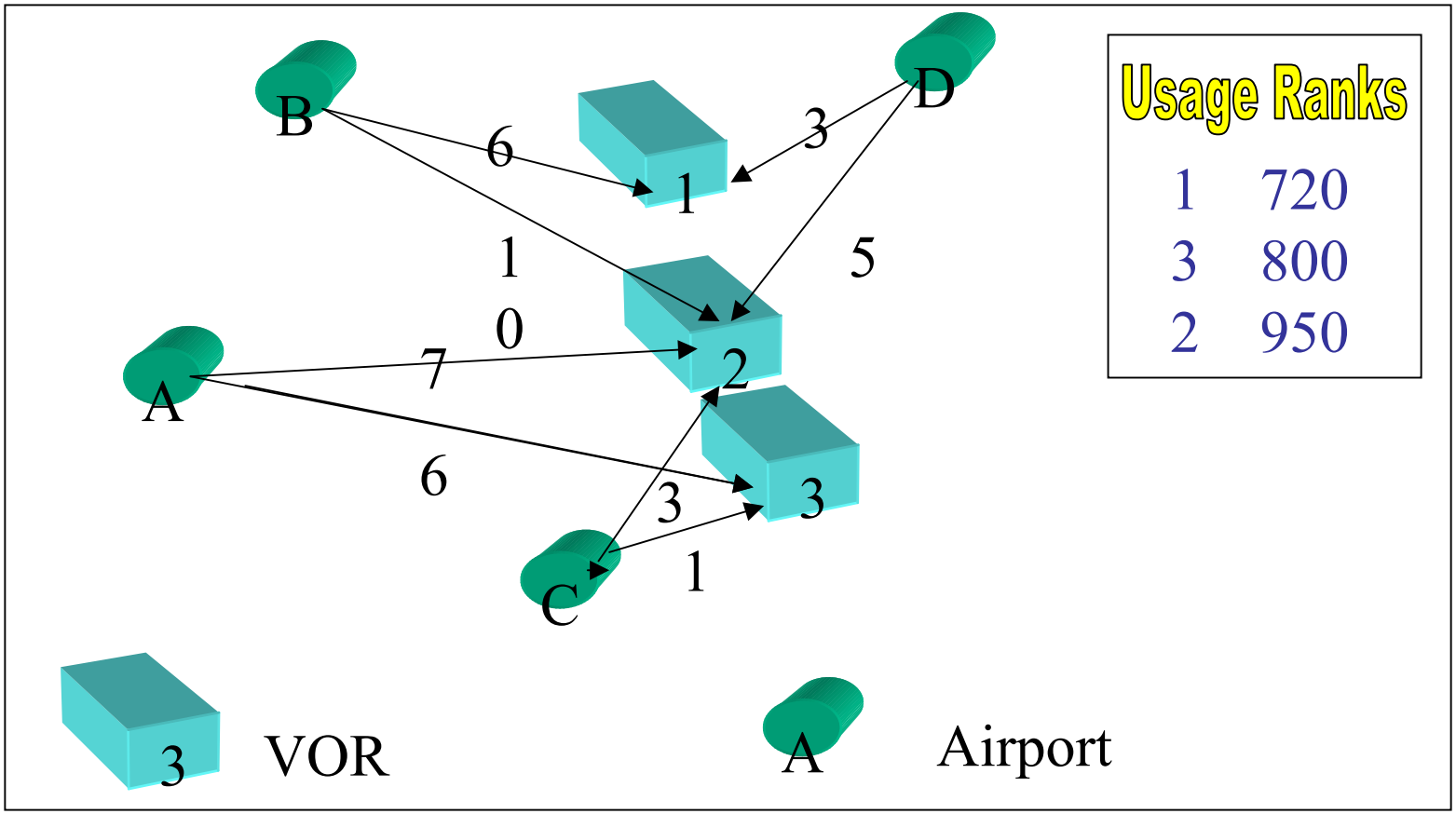
Backup Slides

Avionics Equipage Rate (2011)

Aircraft	User Class	Percent Equipped by 2011
Average Air Carrier	C	80%
Average Freight	F	75%
Average Military	M	85%
Average Air Taxi	T	80%
Average GA	G	75%
Other	O	75%

Table 3-1: Assumed SATNAV Avionics Equipage Rates

Example

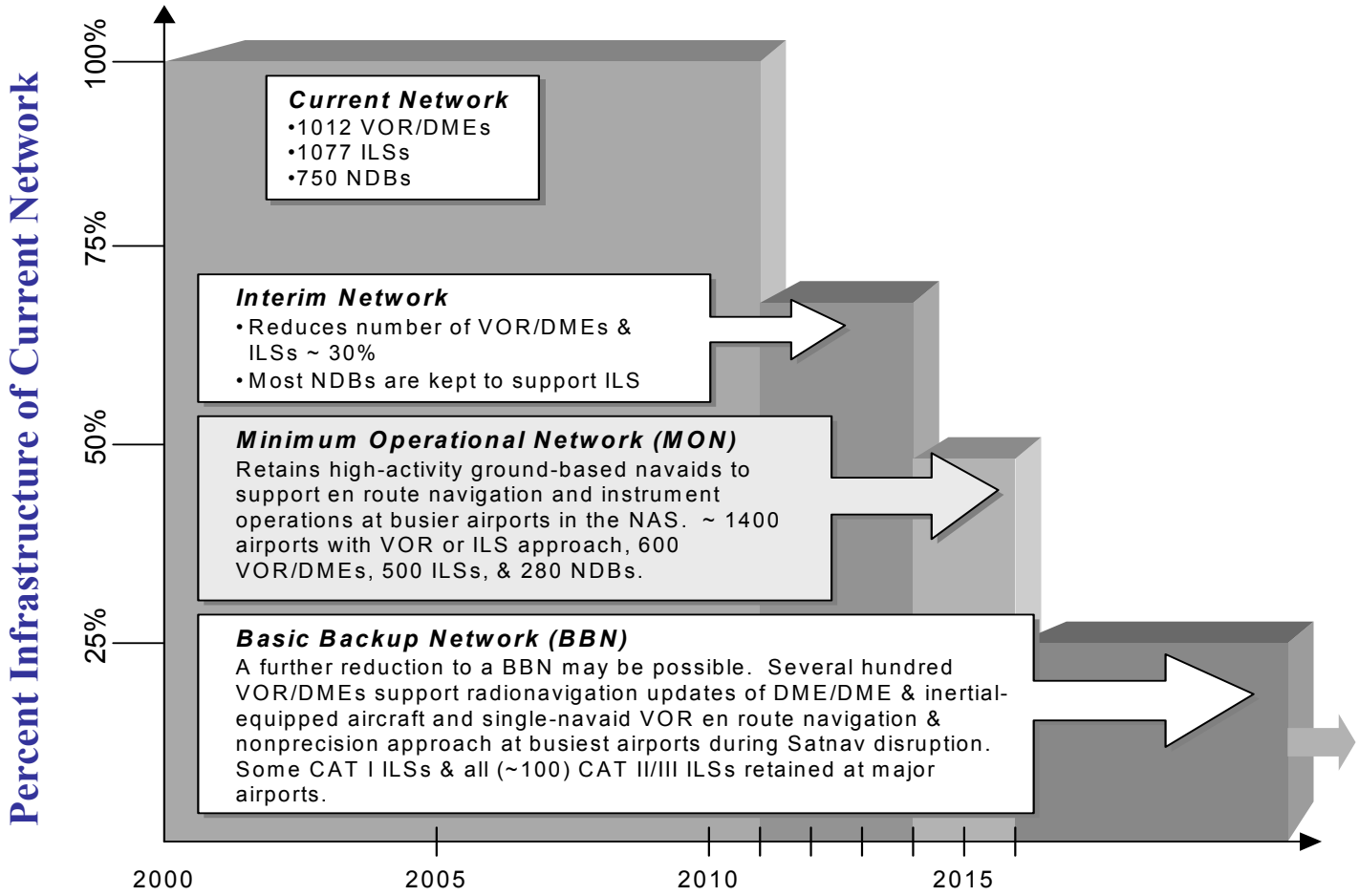


Example of how rank ordering VORs, based on current usage, can provide the wrong answer.

Why an Optimization/Heuristic Model?

- If you were to study all possible combinations, you would have to examine 2^{1000} different combinations!!!
- Using one day to study each case results in 3.93e + 298 years to complete the task.
- A fully automated process which studies each case for only 5 minutes, still needs 1.02e + 296 years to complete the task.

Phase Down Strategy



Operating Costs

Aircraft Class	Average Aircraft Hourly Airborne Operating Cost	Average Airborne Speed	Operating Cost/Mile
Air Carrier/Freight	$2762	418	$6.60
Air Taxi	453	232	1.95
General Aviation	310	177	1.75
Military	1,924	437	4.40
Other	310	177	1.75

Table 5-6: Operating Costs

Avionics Reconfiguration Cost

Avionics Reconfiguration Cost	Air Carrier	Air Taxi/Commuter	GA
Cost to equip and maintain WAAS for one year	$77,800	$77,800	$11,600
Average number of flights per aircraft per year	1,105	2,188	90
Cost per flight (one-year amortization)	$70	$36	$129

Table 5-7: Aviation Reconfiguration Cost

Maintenance and Decommissioning Cost

VOR Info	Total Cost per VOR	Daily Cost per VOR
Annual Maintenance Cost	$86,000	$235
Decommissioning Cost	$300,000	$90
Amortization Years	15	
Discount Rate	7%	

Table 5-8: Maintenance and Decommissioning Cost